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## STUDY OF LOW GRAVITY PROPELLANT TRANSFER

FIRST QUARTERLY PROGRESS REPORT FOR PERIOD  
23 JUNE 1970 THROUGH 22 SEPTEMBER 1970

**GENERAL DYNAMICS**  
*Convair Division*

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28 September 1970

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Prepared by  
CONVAIR AEROSPACE DIVISION OF GENERAL DYNAMICS  
San Diego, California

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## TABLE OF CONTENTS

	<u>Page</u>
1 INTRODUCTION AND SUMMARY	1-1
2 STUDY GROUND RULES	2-1
3 PRELIMINARY SYSTEM SCREENING	3-1
3.1 HIGH PRESSURE SUPPLY	3-1
3.2 INTERMEDIATE PRESSURE SUPPLY	3-4
3.2.1 Surface Force Systems	3-8
3.2.1.1 Capillary System	3-8
3.2.1.2 Dielectrophoretic System	3-10
3.2.2 Positive Expulsion Systems	3-12
3.2.2.1 Bladders	3-13
3.2.2.2 Metallic Bellows	3-16
3.2.2.3 Diaphragms	3-18
3.2.3 Dynamic Force Systems	3-20
3.2.4 Evaporation System	3-25
3.2.5 Overall System Comparisons and Recommendations	3-27
4 PROGRAM COST DATA	4-1
5 WORK TO BE PERFORMED	5-1
6 REFERENCES	6-1

## LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1-1	Master Schedule	1-2
2-1	Space Station Major Features	2-2
2-2	Artificial G Configuration	2-3
3-1	Fluid Transfer Characteristics	3-2
3-2	Conventional High Pressure Transfer System	3-5
3-3	Regenerative High Pressure Transfer System	3-6
3-4	Basic High Pressure Vortex System	3-7
3-5	Channel-Reservoir Capillary Control Device	3-9
3-6	Dielectrophoretic Collection System	3-11
3-7	External Pressurized Bladder	3-14
3-8	Bellows Expulsion System	3-17
3-9	Metallic Diaphragm System	3-19
3-10	Paddle Type Vortex System	3-21
3-11	Jet Type Vortex System	3-22
3-12	Liquid Vaporization System	3-26

## LIST OF TABLES

<u>Table</u>		<u>Page</u>
3-1	Low Gravity Transfer Methods for Cryogenic Fluids	3-3
3-2	Subcritical System Comparison Data (42.5 Ft <sup>3</sup> LO <sub>2</sub> Tank)	3-28
3-3	Subcritical System Comparison Data (42.5 Ft <sup>3</sup> LH <sub>2</sub> Tank)	3-29

## INTRODUCTION AND SUMMARY

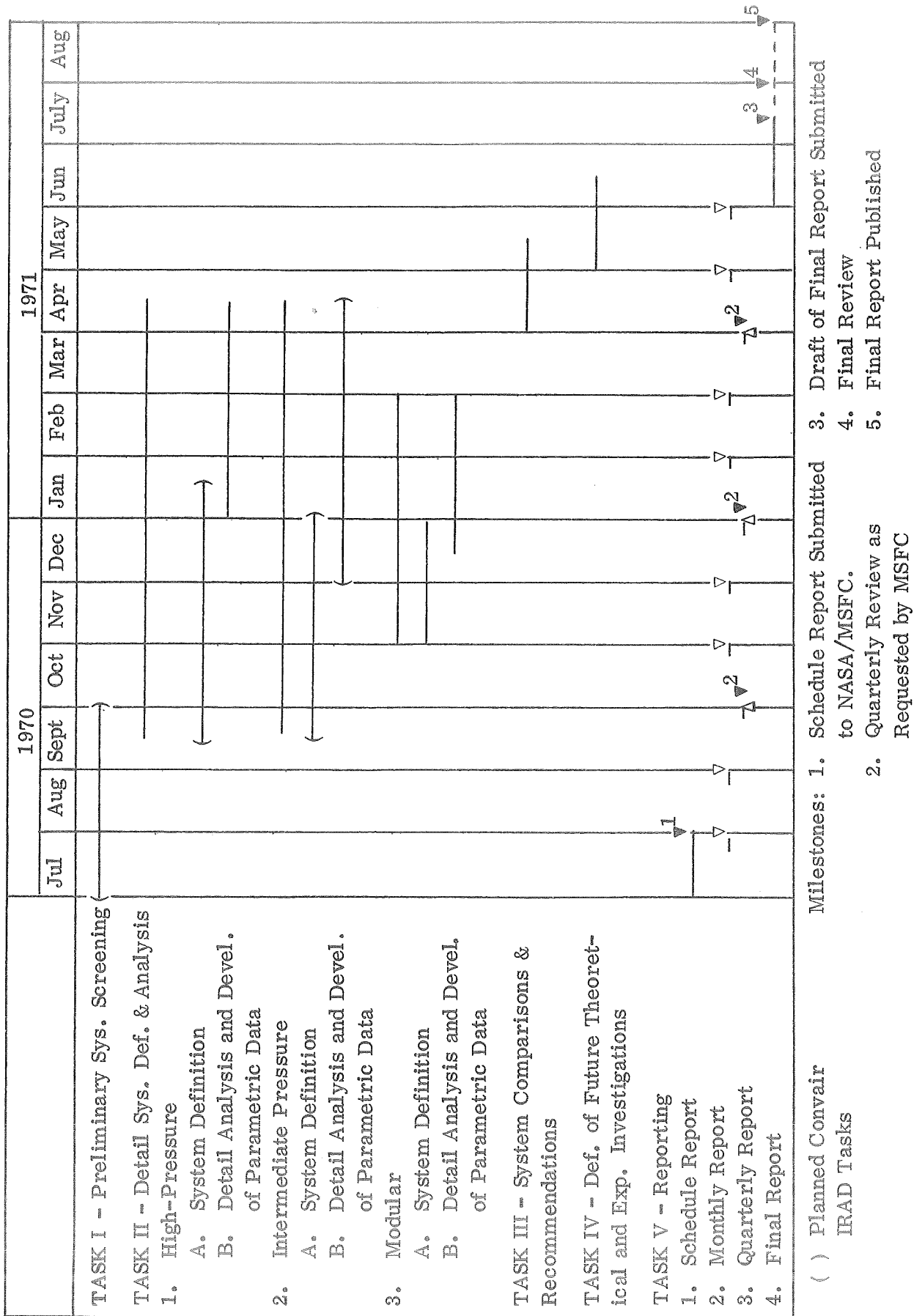
The basic objective of the present program is to perform an analytical assessment of potential methods for replenishing the auxiliary propulsion, fuel cell and life support cryogenics aboard an orbiting space station. This report covers the work performed during the first quarter of the program. During this period a schedule report was prepared and submitted to NASA-MSFC (Reference 1) and the ground rules to be used in the study were reviewed and finalized. For easy reference the program schedule and task outline is presented in Figure 1-1. This schedule also shows related low gravity fluid transfer tasks to be performed under the Convair IRAD program.

Under the Convair IRAD program a screening analysis was accomplished with respect to potential supply methods to determine those most applicable to the replenishment of space station cryogenic fluids. A complete system is taken to consist of supply storage, transfer, and receiver tank fluid conditioning (pressure and temperature control). In terms of supply storage the systems considered in the present program are high pressure (storage above critical), intermediate pressure (subcritical) and modular (transfer of tanks). A matrix of system combinations initially considered is presented in Table 3-1. A preliminary screening has been accomplished on the basis of eliminating systems and/or operations having low safety, low development potential, excessive weight and/or high complexity. Safety and development potential are the two most important criteria.

In the case of the high pressure systems, essentially all comparisons are integrally dependent on thermodynamic and fluid properties associated with the receiver, transfer line and supply. That is, unlike the subcritical systems where the fluid state is essentially fixed for different supply concepts, the high pressure fluid state is an integral part of the supply, transfer and receiver tank control processes. In order to properly determine heating, cooling and residual gas requirements a computer program will be developed to handle the integrated high pressure transfer process. The program will be derived from existing programs presently applicable to individual receiver, supply and transfer line analyses. This program will be applicable to both screening and detail definition and analysis tasks. The high pressure screening analysis will thus be accomplished at the beginning of the detail definition task scheduled to start during the next reporting period.

The initial screening task has essentially been completed for the intermediate pressure or subcritical systems. In performing the comparison analyses the subcritical systems were categorized as follows.

Figure 1-1. Master Schedule





- a. Surface Force Systems - Relying on surface tension or electrical force differences between the liquid and vapor to orient or collect the liquid for transfer.
- b. Positive Expulsion Systems - Providing an essentially impermeable barrier between the pressurant and fluid to be transferred.
- c. Dynamic Force Systems - Where the fluid is forced to move in a manner such that the liquid orientation is known and transfer can be accomplished.

An additional system was also considered where the liquid is vaporized and transferred as a saturated gas. Analysis showed that energy requirements and resulting hardware weights required for vaporization and receiver bottle conditioning were excessively high and, therefore, this system was eliminated from further consideration.

It is noted that for each of the system types listed in a. through c. above, the auxiliary system requirements and design problems as to pressurization and/or pumping, thermal protection and venting, line and receiver tank chilldown and general receiver tank fluid conditioning will be similar within each category. It was therefore deemed desirable to choose a representative system from each category for further overall detail system definition, analysis and comparisons.

Based on state-of-the-art, safety and weight comparisons the following systems were chosen for further detail definition and analysis.

- a. Surface tension or capillary containment system using screens.
- b. Metallic bellows for positive expulsion.
- c. Fluid vortexing within a restrained tank in order to orient the liquid at the outer periphery for transfer.

The surface tension system was chosen over the dielectrophoretic surface orientation system primarily on the basis of potential safety. Weights and state-of-the-art of the two systems are comparable, however, for use in oxygen there is still some question of electrical breakdown and associated combustion hazard associated with the dielectrophoretic system.

In the case of the positive expulsion methods the metallic bellows was chosen as the only system potentially capable of meeting the number of expulsion cycles desired (20 to 40 cycles) for the station resupply application. Also, even though somewhat heavier than other methods the potential of developing a reliable and predictable system for use with cryogenics is felt to be higher with the bellows system. It is noted that other methods such as metallic and/or non-metallic diaphragms and bladders can be considered and compared with the bellows system even though not having a total life comparable to that of the station. This comparison

would be on the basis of total cost and would take account of replacing such systems or expulsion components after a number of flights. The impact on the total transfer operation of developing such positive expulsion systems will be assessed and reported as part of the detail analysis and comparison tasks.

In the case of dynamic liquid control fluid vortexing was chosen as that most applicable to the station resupply from a shuttle vehicle, since linear acceleration or rotation of the entire shuttle and station was not considered practical. Rotation of the bottle within the payload is possible, but was not considered desirable in comparison with fluid vortexing due to the requirement for a stationary to rotating fluid connection.

Variations with respect to the modular transfer concept, as illustrated in Table 3-1, are considered to be detail design perturbations which will be resolved during the detail definition and analysis task.

Analytical data and further discussions associated with the work accomplished during the first quarter are presented in the following sections.

## STUDY GROUND RULES

The study ground rules have been chosen to provide a scope of work such that a reasonably general investigation of low gravity fluid transfer can be accomplished within the specific requirement to replenish any cryogenics which may be considered for use aboard an earth orbiting space station.

For ready access, current data obtained from References 2 and 3 and which are pertinent to the present program are presented below.

A sketch of the space station, pointing out its major features, is shown in Figure 2-1. Cryogenics may be replenished from the shuttle docked to any of the five docking ports shown in Figure 2-1. For a 35 day period out of the first 90 days into the flight an artificial G experiment will be conducted by rotating the space station in the configuration shown in Figure 2-2. Rotational acceleration will be obtained by using the space station RCS. Cryogenics for RCS spin-up of the space station for the artificial G experiment will be drawn from a supply module docked to one of the five docking ports. At present it is proposed to use the same cryogenic storage configuration aboard the shuttle for this supply as will be used on the station.

The space station is being designed for a lifetime of ten years with a circular earth orbit of 240 - 246 nautical miles at a 55° inclination angle. The space station must be capable of independent operation for periods up to six months. Possible cryogenics to be required by the space station are  $\text{LN}_2$ ,  $\text{LO}_2$  and  $\text{LH}_2$ .

For redundancy in the event of meteoroid impact, half of the cryogenics will be stored at one end of the space station and an equal quantity of each cryogen will be stored at the opposite end of the station. All cryogen storage containers must be capable of being replenished from a vehicle docked to any one of the five docking ports. All cryogen storage containers are presently of a common size and are spherical containers with volumes of 42.5 ft<sup>3</sup>. Eight tanks are used for hydrogen storage, two tanks for oxygen storage and two tanks for nitrogen storage. All such storage is subcritical. The normal operating pressure is 100 psia with a maximum design pressure of 150 psia. Heat leak to the  $\text{LN}_2$  tanks must be no greater than that required to boil off 100% of the  $\text{LN}_2$  in six months.  $\text{LO}_2$  and  $\text{LH}_2$  tank heat leak must be no greater than required to boil off 50% of the respective fluids in six months.

From Reference 3 the total fluid quantities are 1096 lb of  $\text{LH}_2$ , 2480 lb of  $\text{LO}_2$  and 3150 lb of  $\text{LN}_2$ . In all cases the  $\text{LH}_2$  and  $\text{LO}_2$  will be propellant grade fluids. Resupply is assumed to occur at a maximum of every six months. All tanks are of a common

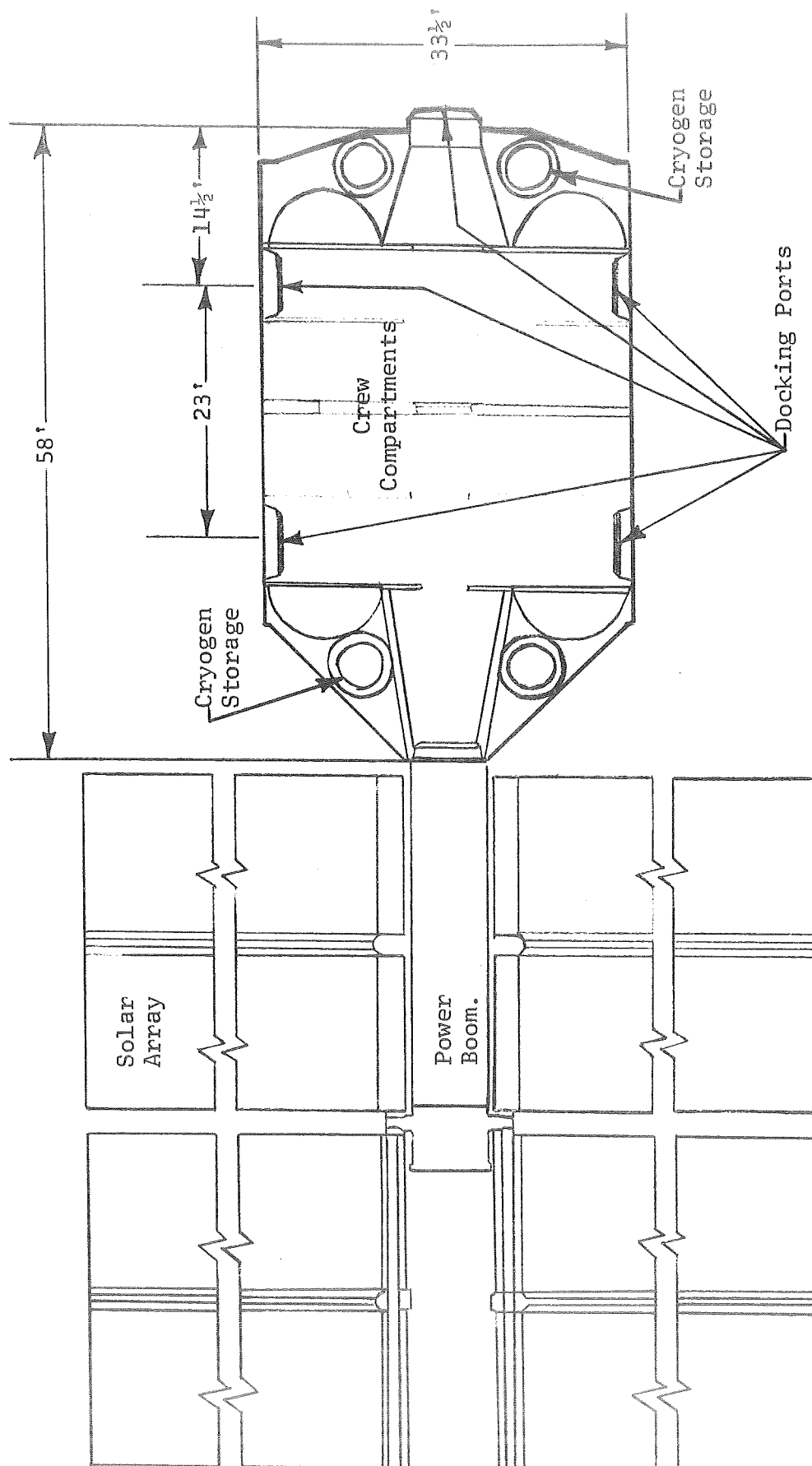
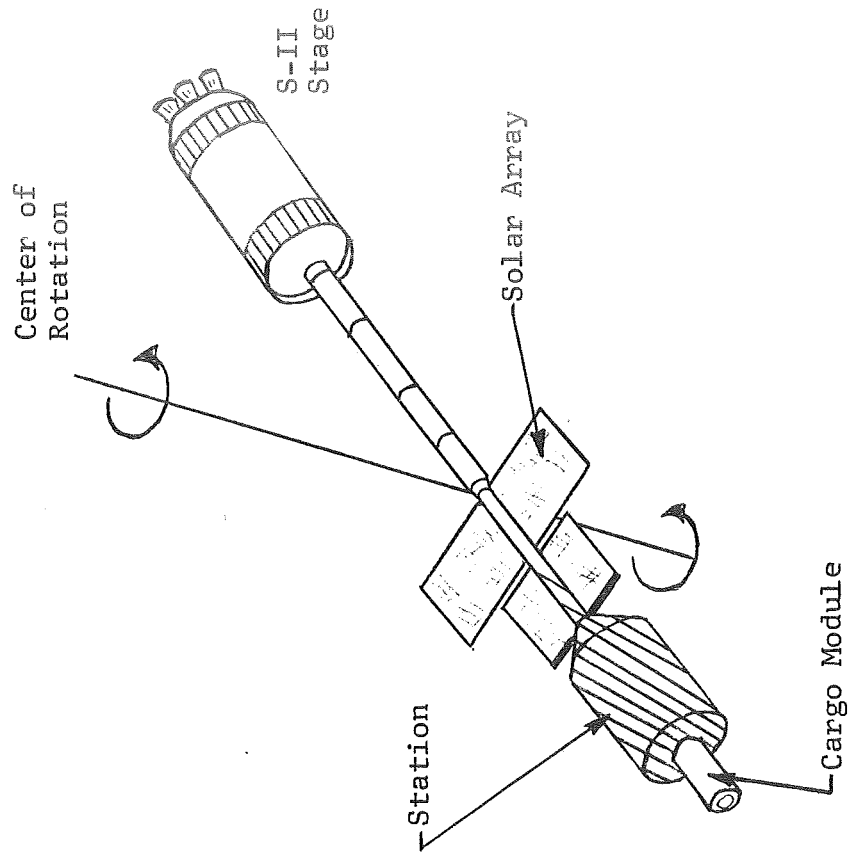
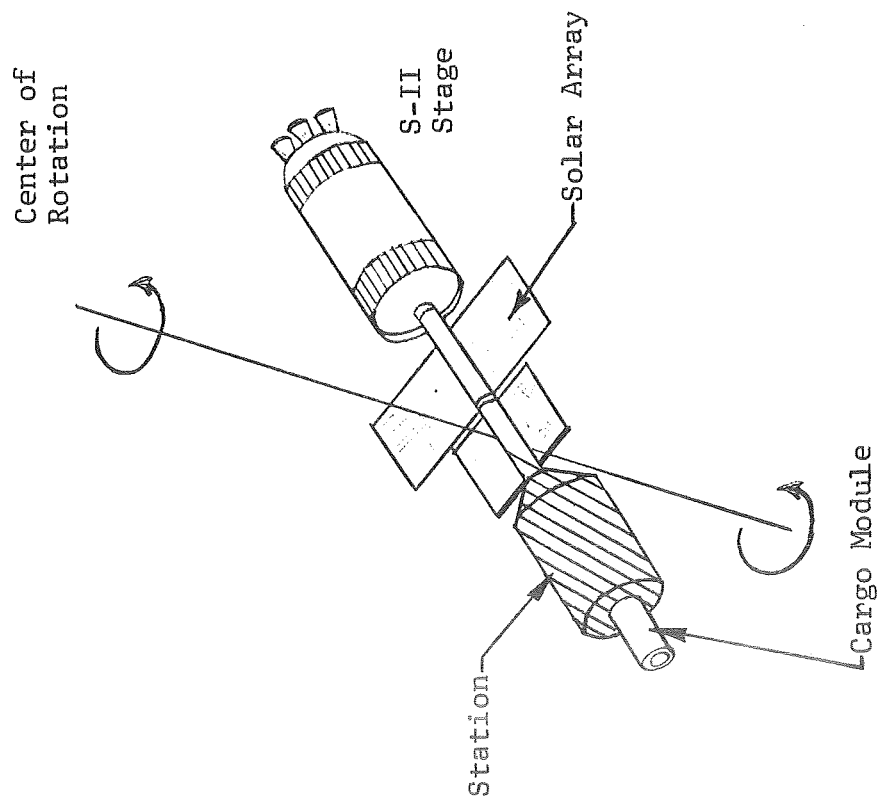


Figure 2-1. Space Station Major Features



Extended S-II



Docked S-II

Figure 2-2. Artificial G Configuration

design and are assumed to be insulated with approximately 8 inches of high performance insulation (HPI). Also, the tanks are located external to the pressurized cabins in an uncontrolled environment. In all cases fluid may be supplied to the user function as a saturated vapor or liquid. The individual tank weight is 225 pounds.

The shuttle supply vehicle will have a maximum acceleration of 3 G's. The thermal environment within the cargo compartment is undefined. It can be assumed that the propellant tanks for space station resupply are located inside the shuttle cargo compartment and can be topped off until 1/2 hour before liftoff. The fluid would be transferred from the shuttle to the space station at some time interval within seven days after docking the shuttle to the space station.

The maximum disturbing acceleration during the transfer operation is  $10^{-4}$  G's. Based on the above data and a desire to cover the full range of future resupply applications the following specific ground rules will be used in actually generating the analytical data. The data below represents a compilation and screening of the information contained in References 2 through 5.

1. The resupply fluids will be  $H_2$ ,  $O_2$  and  $N_2$ .
2. In each case both subcritical and supercritical receiver or space station tanks will be considered.
3. Transfer line lengths will range from 20 to 200 feet.
4. The maximum disturbing acceleration which can occur in any direction during transfer is  $10^{-4}$  G's.
5. Crew tasks will be minimized and crew safety is a prime consideration.
6. Time from final topping of the supply bottles on the ground to start of transfer will be anywhere from 4 hours to 7 days.
7. Maximum boost acceleration is 3 G's.
8. The shuttle cargo compartment during boost may be either pressurized or unpressurized.
9. The space station bottles are in unpressurized areas as shown in Figure 2-1 and allowable heat leaks are such as to require venting of 100% of  $LN_2$  and 50% of  $LO_2$  and  $LH_2$  when maintaining a constant storage pressure over the system operating life.
10. Heat sinks below 500°R are not available on the station for bottle cooling, and any such cooling must be a part of the supply system or proposed as an addition to the space station.

11. The station life is 10 years.
12. Full replenishment will be assumed to occur every six months with the capability of 50% replenishment every 90 days.
13. The individual receiver bottles will be assumed to be anywhere from empty to one-half full at the initiation of transfer.
14. Parametric studies of receiver or space station bottle sizes will range from internal diameters of 25 to 150 inches.
15. The number of bottles to be filled for each fluid will range from one to sixteen.
16. The total fluid quantities considered will range from 500 to 5000 lb of  $\text{LH}_2$  and 1000 to 10,000 lb each for  $\text{LO}_2$  and  $\text{LN}_2$ .
17. Any modifications or design features required of the receiver bottles for efficient operation of a particular supply mode will be defined during the study.
18. The supply bottles are assumed fixed in the shuttle cargo module during fluid transfer.
19. In all cases propellant grade fluids will be supplied.
20. The maximum allowable time for the transfer operation is 24 hours.

## PRELIMINARY SYSTEM SCREENING

A screening analysis has been accomplished with respect to potential low gravity fluid transfer methods to determine those most applicable to the replenishment of the cryogenics aboard an orbiting space station. This work was performed, as planned, under the 1970 Convair IRAD program. A complete system is taken to consist of supply storage, transfer, and receiver tank fluid conditioning (pressure and temperature control). These various functions are illustrated schematically in Figure 3-1. In terms of supply storage the basic systems to be considered are high pressure (greater than critical), intermediate pressure (less than critical), and modular (transfer of the tanks). A matrix of typical system combinations to be considered in the overall study is illustrated in Table 3-1. The preliminary screening was accomplished on the basis of eliminating systems and/or operations having low safety, excessive weight and/or low development potential. Results of the preliminary screening task are presented in the following paragraphs.

## 3.1 HIGH PRESSURE SUPPLY

As shown in Table 3-1, the potential storage pressures are classified into two ranges. The most obvious is that commonly classified as supercritical (pressures of critical to approximately 1,500 psia for the particular fluids under consideration). In this case transfer or expulsion of the supply fluids is nominally accomplished by heating. The supply pressure is maintained with either an internal heater and mixer or by an external heater and closed-loop circulation pump. The use of pressures higher than near critical may allow a significant amount of transfer to be accomplished by a simple blow-down of the storage bottle, with a possible reduction in auxiliary cooling requirements. As an example, the additional fluid carried in the supply bottle at higher pressures could be used during line and receiver bottle chilldown operation as required.

It is noted that the major concern with the high pressure systems is the fact that significant energy must, in general, be added to the supply in order to transfer any significant quantity of fluid. This energy must then be effectively removed from the transferred fluid or receiver tank in order to obtain a high final density in the receiver. Conventional refrigeration techniques applied to such cooling result in a very high weight penalty for such cooling, especially at hydrogen temperatures. Based on the importance of the energy processes or heating and cooling requirements a categorization of the high pressure transfer methods for analysis will be on the basis of the methods used to provide such overall energy control.

On this basis the systems to be considered in the analysis are divided into those using essentially conventional supply heating and receiver cooling methods and those



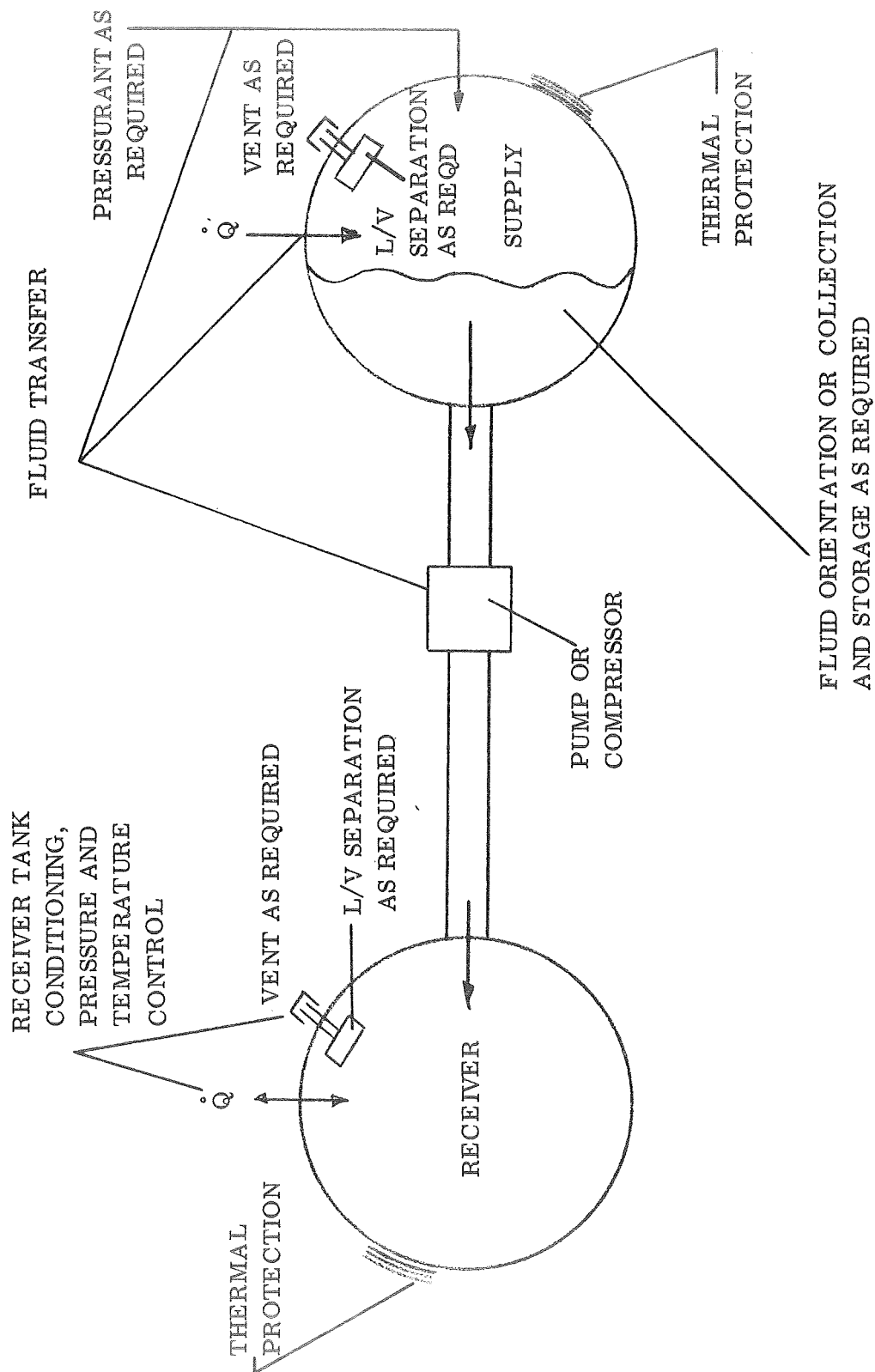


Figure 3-1. Fluid Transfer Characteristics

Table 3-1. Low Gravity Transfer Methods for Cryogenic Fluids

	TRANSFER METHODS						RECEIVER TANK FLUID CONDITIONING			
	LIQUID PUMP	GAS COMPR	GAS PRESS	BLOW-DOWN	HEATING		COOLING	VENTING		NON-VENT
					EXT. LOOP	INT. LOOP		WITH L/V SEP.	NO SEP.	
SUPPLY STORAGE										
High Pressure (Critical to 1500 psia)		x		x	x	x	x	x	x	x
(1500 to 10,000 psia)		x		x	x	x	x	x	x	x
Intermediate Pressure Capillary Containment	x		x				x	x		x
Dielectrophoresis	x		x				x	x		x
Bladder	x		x				x	x		x
Metal Bellows	x		x				x	x		x
Diaphragms	x		x				x	x		x
Fluid Vortexing	x		x				x	x		x
No Containment		x			x	x	x	x		x
Modular Transfer										
Concentric Connections										
Clustered Connections										
Rigid										
Flexible										

employing somewhat non-conventional methods and generally using the supply fluid in the refrigeration cycle to reduce overall weight. Typical systems are illustrated schematically in Figures 3-2 and 3-3. The actual initial storage pressure to be used in each case will then be optimized on the basis of weight and energy.

In the case of the high pressure systems, essentially all comparisons are integrally dependent on thermodynamic and fluid properties associated with the receiver, transfer line and supply. That is, unlike the subcritical systems where the fluid state is essentially fixed for different supply concepts, the high pressure fluid state is an integral part of the supply, transfer and receiver tank control processes. In order to properly determine heating, cooling and residual gas requirements a computer program will be developed to handle the integrated high pressure transfer process. The program will be derived from existing programs presently applicable to individual receiver, supply and transfer line analyses. This program will be applicable to both screening and detail definition and analysis tasks. The high pressure screening analysis will thus be accomplished at the beginning of the detail definition task scheduled to start during the next reporting period.

Preliminary analysis, however, indicates that conventional cooling techniques will result in very high weight penalties for the basic high pressure system. Therefore an attempt will be made to define regenerative systems having reasonable weight penalties. One such system which will be further considered is shown in Figure 3-4. This system utilizes the Hilsch tube vortex concept to provide heating of the supply tank while allowing transfer of a relatively cool fluid to the receiver tank. The operating power for the system comes primarily from the pressure difference between the supply and receiver tanks which is used to accelerate the fluid within the vortex tube.

### 3.2 INTERMEDIATE PRESSURE SUPPLY

The primary problem with the intermediate or subcritical supply methods is that under low gravity some manner of orientation or collection of the liquid for transfer must be employed. Therefore, the subcritical systems are characterized by the method used for liquid orientation. In performing the comparison analysis orientation methods were categorized as follows.

1. Surface Force Systems - Relying on surface tension or electrical force differences between the liquid and vapor to orient or collect the liquid for transfer.
2. Positive Expulsion Systems - Providing an essentially impermeable barrier between the pressurant and fluid to be transferred.
3. Dynamic Force Systems - Where the fluid is forced to move in a manner such that the liquid orientation is known and transfer can be accomplished.

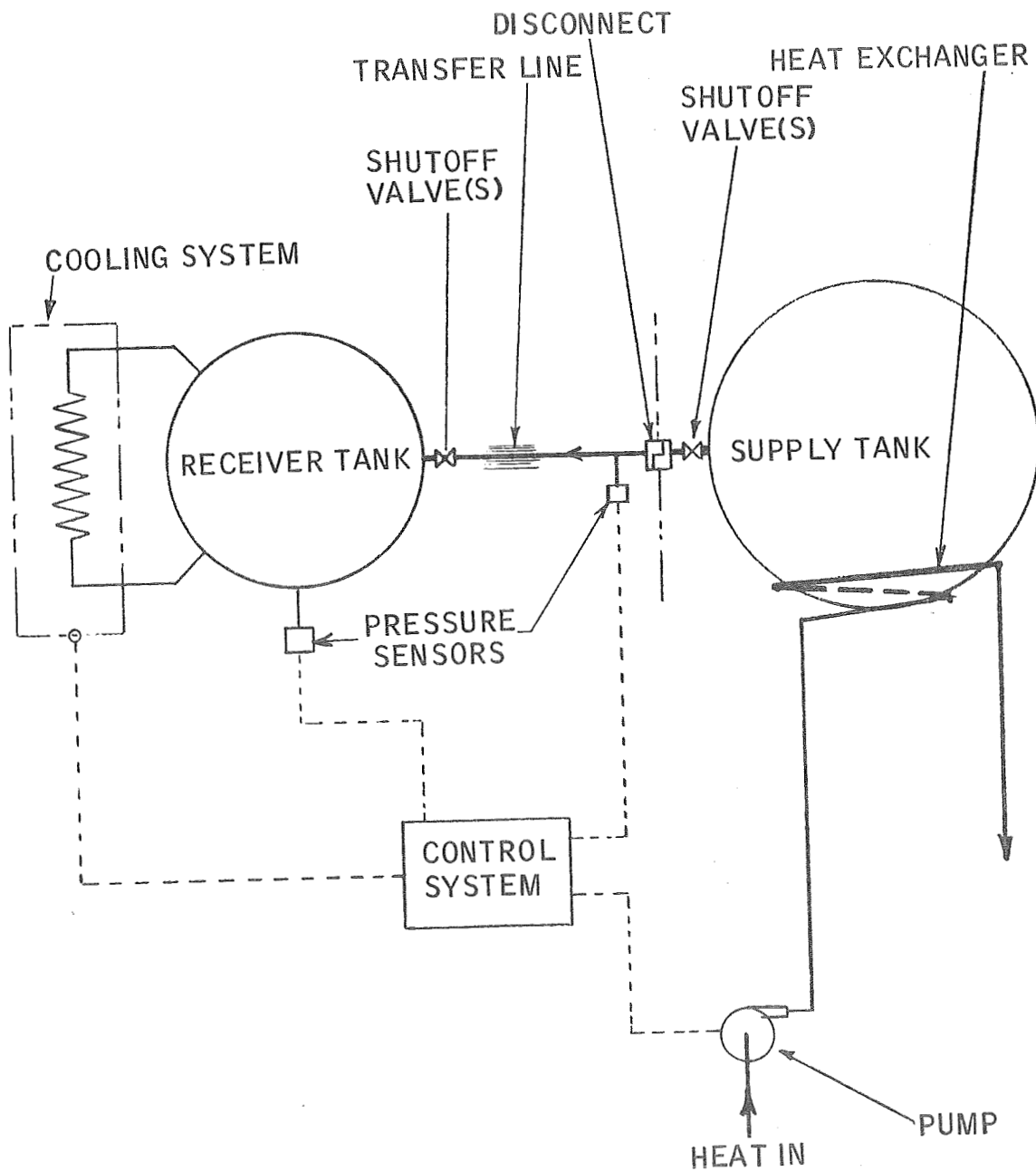


Figure 3-2. Conventional High Pressure Transfer System

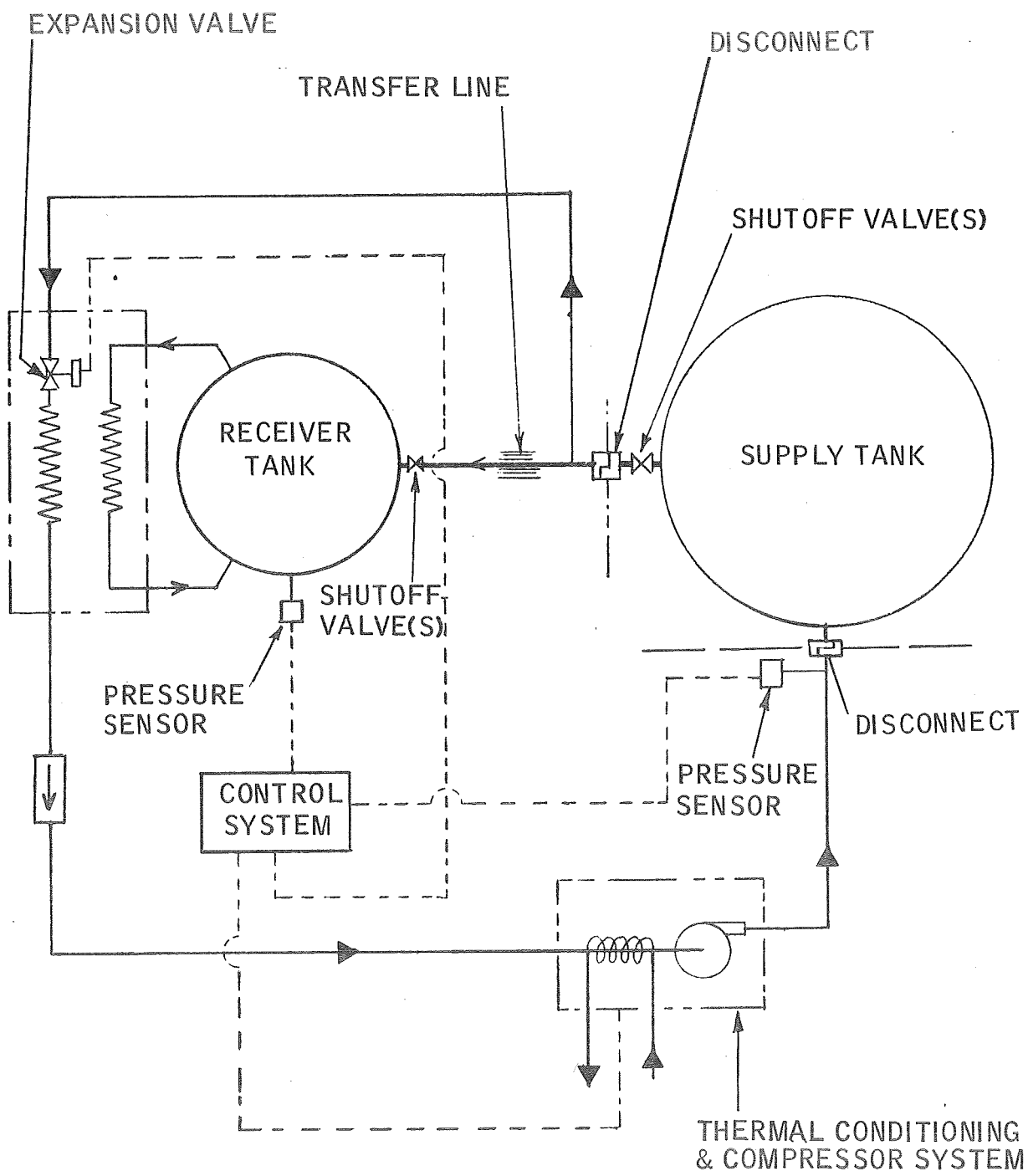


Figure 3-3. Regenerative High Pressure Transfer System

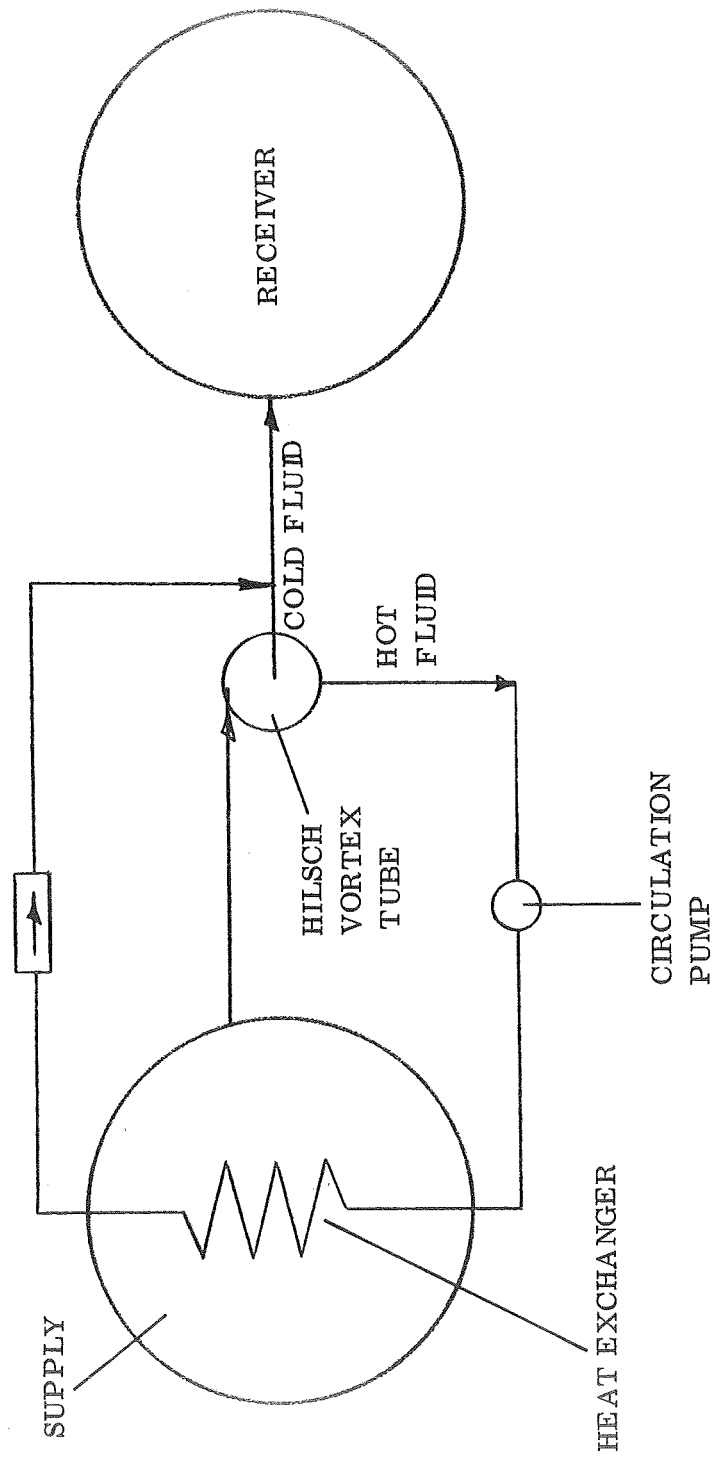


Figure 3-4. Basic High Pressure Vortex System

An additional system was also considered where the liquid is vaporized and transferred as a saturated gas.

It is noted that for each of the system types listed above, the auxiliary system requirements and design problems as to pressurization and/or pumping, thermal protection and venting, line and receiver tank chilldown and general receiver tank fluid conditioning will be similar within each category. Thus in performing the screening analysis such auxiliary system requirements were not included in the data developments. The data generated are therefore primarily used for system comparisons within each category.

In performing the screening a nominal supply tank volume of 42.5 ft<sup>3</sup> was assumed and the desirable operating life of the system was taken to be 40 cycles. Systems having less capability were considered on the basis of periodic replacement. Both LO<sub>2</sub> and LH<sub>2</sub> were considered as the transfer fluids and the maximum transfer time was taken as 24 hours.

The initial screening task has been completed for the subcritical systems and the results are presented in the following paragraphs. General state-of-the-art and safety discussions and background data developments are presented in Paragraphs 3.2.1 through 3.2.4. Paragraph 3.2.5 presents overall weights, efficiencies and relative evaluations of all the systems considered.

**3.2.1 SURFACE FORCE SYSTEMS.** Two such systems were considered; (1) a capillary collection system employing screens and (2) a dielectrophoretic system using dielectric properties of the fluid to effect collection. The systems are individually discussed below.

**3.2.1.1 Capillary System.** The system analyzed is shown in Figure 3-5. The liquid collector channels are designed to maintain continuous contact with the tank liquid while the cylindrical reservoir provides liquid flow in the event a disturbing acceleration forces the channels to be momentarily uncovered from the main liquid pool. The basic concept used in the present comparisons was developed under Contract NAS8-21465. The detailed configuration design data are presented in Reference 6. The weight of this system as applied to a 52 inch LO<sub>2</sub> tank is estimated to be on the order of 30 lb. Expulsion efficiency is estimated to be 98%, and the volumetric efficiency 99.5%.

The primary advantage of such devices are that they are lightweight, generally passive and can be used for a number of cycles of operation. Such devices have previously been applied to non-cryogenic propellant acquisition for engine restart purposes. Using cryogenic fluids introduces thermodynamic and heat transfer problems which can significantly effect system design. The primary problem is to prevent vapor generation within the capillary device from causing a breakdown in the capillary barrier such that a direct vapor path is formed between the ullage and the tank outlet. Also, in the case of a continuous collection system operating at low gravity, communication between the tank outlet and liquid pool must be maintained throughout the

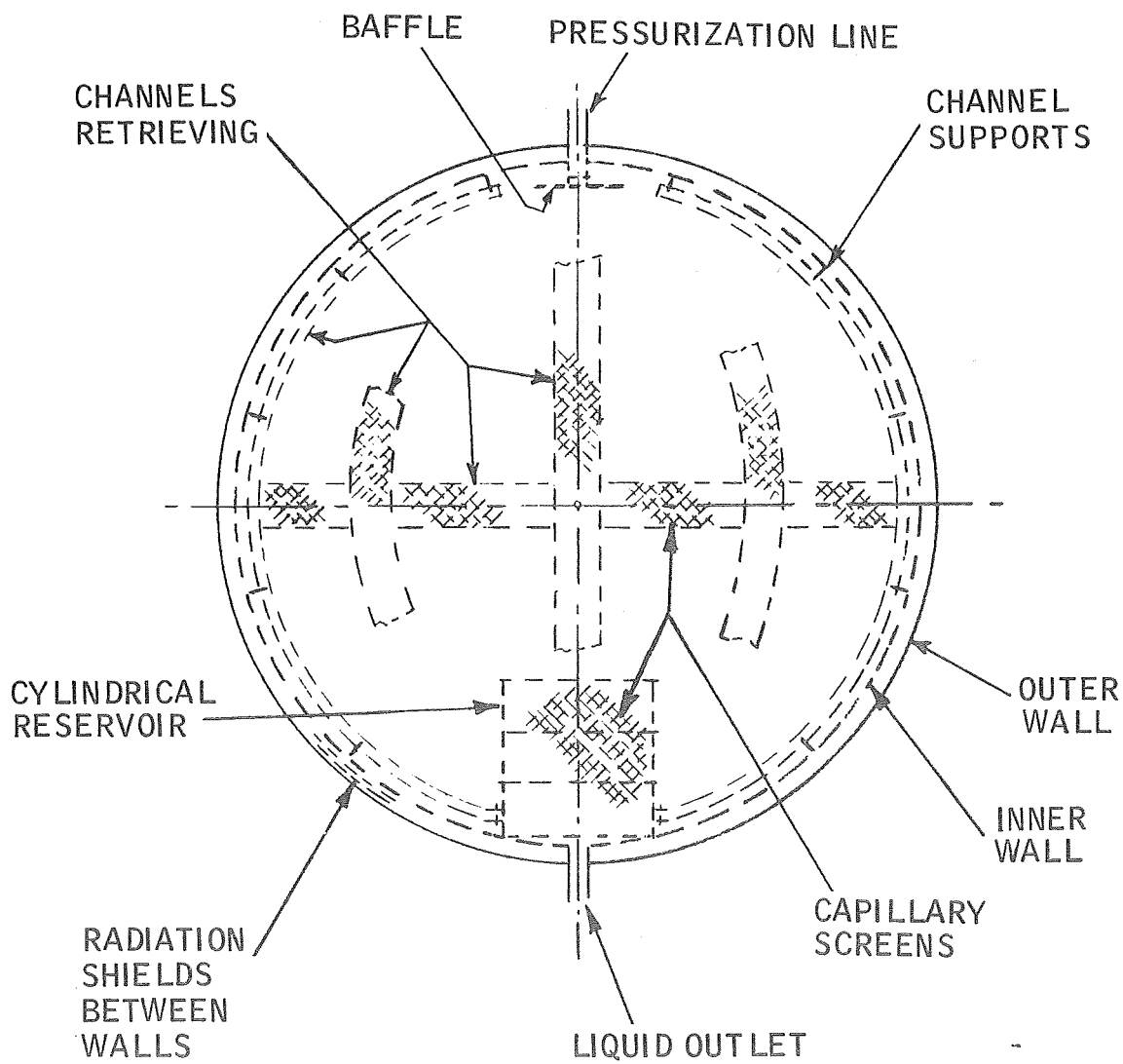


Figure 3-5. Channel-Reservoir Capillary Control Device



transfer in order to minimize residuals. In general the residuals for the present collection system will be greater than that of an orientation system used for engine start since bottoming acceleration build up will not occur in the present transfer application. The above problems were analyzed under contract NAS8-21465 and the overall results are presented in References 6, 7 and 8.

The resulting design utilizes the vent fluid to control the heat leak into the capillary device such that harmful vapor formation is prevented and the reservoir shown in Figure 3-5 assures continuous communication of the liquid with the tank outlet.

Analysis indicates that such design approaches will result in a reliable system for the transfer application and such systems would be good for the full number of transfers desired. Fluid cleanliness must, however, be maintained at a high level in order to prevent screen clogging from occurring over a period of time. In this regard periodic cleaning may be necessary. This will be considered further under the detail definition and analysis tasks.

3.2.1.2 Dielectrophoretic System. Dielectrophoresis is defined as the motion of matter caused by polarization effects in a nonuniform electric field. This electrical phenomenon may be used to orient and control a large class of dielectric fluids, including cryogenic hydrogen, oxygen and nitrogen. For the present application this orientation is accomplished by locating electrodes (electrostatic condensers) within the transfer tank such that the liquid is moved and drawn into the space between the high potential and ground electrodes.

A considerable amount of analytical and test data have been generated on this concept for use with LH<sub>2</sub> and LO<sub>2</sub> as applicable to the present program. The most complete information was found in References 9 through 12. Based on the information obtained from these references the use of a ribbon electrode configuration, as shown in Figure 3-6, is considered the most promising. The system weight (including power supplies), expulsion efficiency, and volumetric efficiency were estimated to be 40 lb, 99% and 99.5% respectively. Weight data were determined from the information contained in Reference 10.

The primary advantage of this system over the capillary screen device is that with the dielectrophoretic system positive orientation is applied to the liquid such that vapor bubbles are forceably expelled from the drain. Thus vaporization within the electrode or expulsion channels is not a potential problem as it is with the surface tension device.

The main concern with the dielectrophoretic system is the complexity associated with required high voltage feed-throughs and power supplies. Also, there is some question of LO<sub>2</sub> compatibility where electrical discharges may occur. Furthermore the potential arcing of electrodes is forever present. Several NASA studies have been performed in order to demonstrate the safety of such systems. The data are presented in References 10 and 12. The latest testing most applicable to the present program was

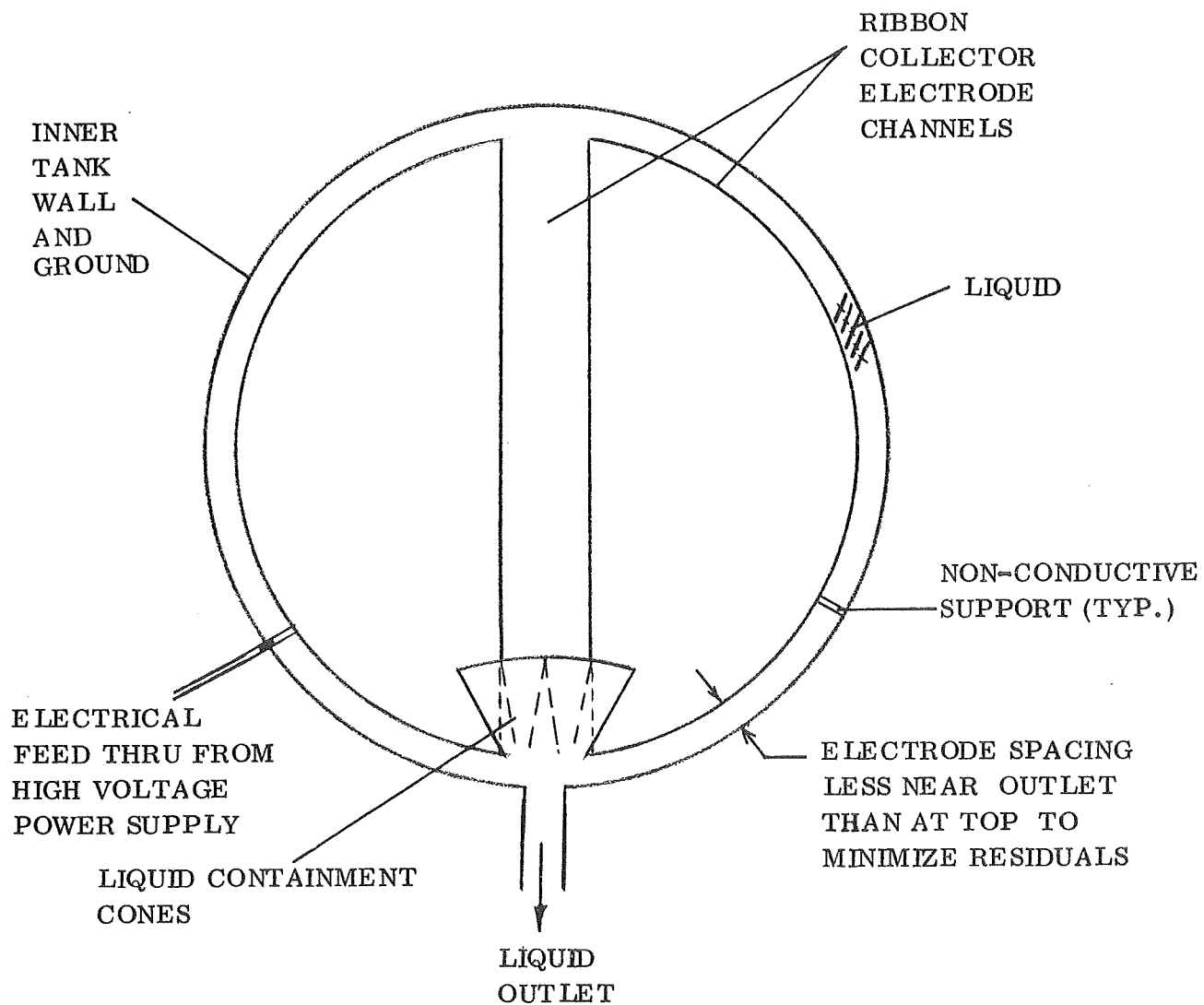


Figure 3-6. Dielectrophoretic Collection System

performed under contract NAS8-20553 and reported in Reference 12. This report was reviewed by Dr. Sam Kaye of the Convair Scientific Research Department. He has had extensive experience with respect to O<sub>2</sub> and H<sub>2</sub> combustion under NASA contracts NAS8-11405 and NAS8-20350 and under the Convair IRAD program. A summary of his comments is presented below.

1. The data contained did not demonstrate that operating safety in full size tanks can be predicted by subscale tests. The scaling was done only on the basis of breakdown voltage with respect to electrode spacing, pressure and temperature. A very important scaling parameter which was not considered in the analysis is the ratio of enclosed fluid mass or volume to surface area and tank mass. The important consideration here is the rate at which heat to the enclosed mass can be dissipated to the surroundings. A small tank is less likely to accumulate an explosive amount of heat (that required to start combustion of the metal electrodes and/or container) than a large tank.
2. The method of testing was not conducive to obtaining known mixture ratios of propellant gases and helium since the assumption of complete gas mixing, especially with helium and O<sub>2</sub>, would be far from true as their densities are significantly different and no attempt was made to provide mixing. This would, however, only serve to shift the breakdown data curves and should not significantly effect the overall safety analysis.
3. The small sample testing of materials would not necessarily be valid for demonstrating complete safety, for the same reasons as stated in comment (1). Also, arcing time was not given or discussed and this would be an important factor in whether or not a fire could be initiated. Given enough heat, eventually ignition of the electrode and container material could occur.
4. The O<sub>2</sub> testing is considered to be by far the most critical and, due to the failure of the high voltage feedthrough, the test series was cut short such that this series of tests was not conclusive in proving O<sub>2</sub> system safety.
5. Another factor which was not completely analyzed, tested or otherwise accounted for was the specific shape and mass (as effecting system heat up) of the electrodes themselves. These factors can have a significant effect on ignition. Also, electrode shape and manufacture can have a strong effect on breakdown voltage and where it will occur. As an example a burr type of defect can cause a voltage or charge concentration which will cause premature breakdown or arcing at that point.

3.2.2 POSITIVE EXPULSION SYSTEMS. Such systems are designed to provide a positive barrier between the pressurant and fluid to be transferred. Bladder, bellows and diaphragm systems were considered and are discussed below. Pistons were not considered due to their combination of high weight and moving seal problems.

3.2.2.1 Bladders. A significant amount of development work has been accomplished on such systems. The folding type of non-metallic bladder, as shown in Figure 3-7, is considered most applicable to the present program. Such systems have been satisfactorily demonstrated for the expulsion of earth storable fluids and are presently in use with such fluids.

The primary problem with the use of bladders for cryogenic fluid expulsion is in finding materials which are flexible at cryogenic temperatures and which can be incorporated into a satisfactory design. In considering use with LO<sub>2</sub>, considerable work has been done on developing materials and adhesives which are both flexible and LOX compatible under the required operating conditions. The most recent and applicable data with respect to the development of such systems for use with cryogenics was obtained from References 13 through 21. In summary the development has progressed as follows.

Materials and complete system testing was performed in order to determine satisfactory materials and bladder fabrication techniques for the cryogenic application. Satisfactory systems were determined to consist of thin plys (on the order of 0.5 mils) of either Mylar or Kapton laminated together into a multiply configuration.

LO<sub>2</sub> compatibility testing was then performed on the individual materials using the ABMA sensitivity criteria that detonation shall not occur when the material is subjected to an impact of no less than 72 ft-lb. The Mylar did not meet this criteria. However, with proper baking during the fabrication process the Kapton did meet it (Reference 20). In any case, it was felt that in the actual bladder assembly it would be impossible to add enough energy to the bladder material itself in order for detonation to occur.

Subsequent full scale testing was performed where a 30-06 non-ferrous bullet was fired into the bladder tank at high velocity. Both Mylar and Kapton multiply bladders were tested. In these tests the Mylar charred and the Kapton burned. It was felt that these failures were primarily due to the non-LOX compatible adhesives used in the system.

Subsequent investigation and material testing was performed in order to develop a LOX compatible adhesive. This program was considered successful and full scale bladder testing was then continued using the new adhesive. During these tests, again using a non-ferrous projectile, the Mylar did not react and the Kapton showed one reaction out of 12 tests; and in this case (Reference 20) the aluminum tank itself also burned.

This is essentially the current state-of-the-art of LO<sub>2</sub> expulsion bladders. According to the people at Boeing (Reference 20) it is felt that bladders for LO<sub>2</sub> service have been satisfactorily demonstrated. It is felt that such systems should ultimately be good for up to 25 cycles on a reliable and repeatable basis. It is estimated that the number of test cycles would need to be on the order of 50 in order to guarantee a repeatable 25 cycle life.

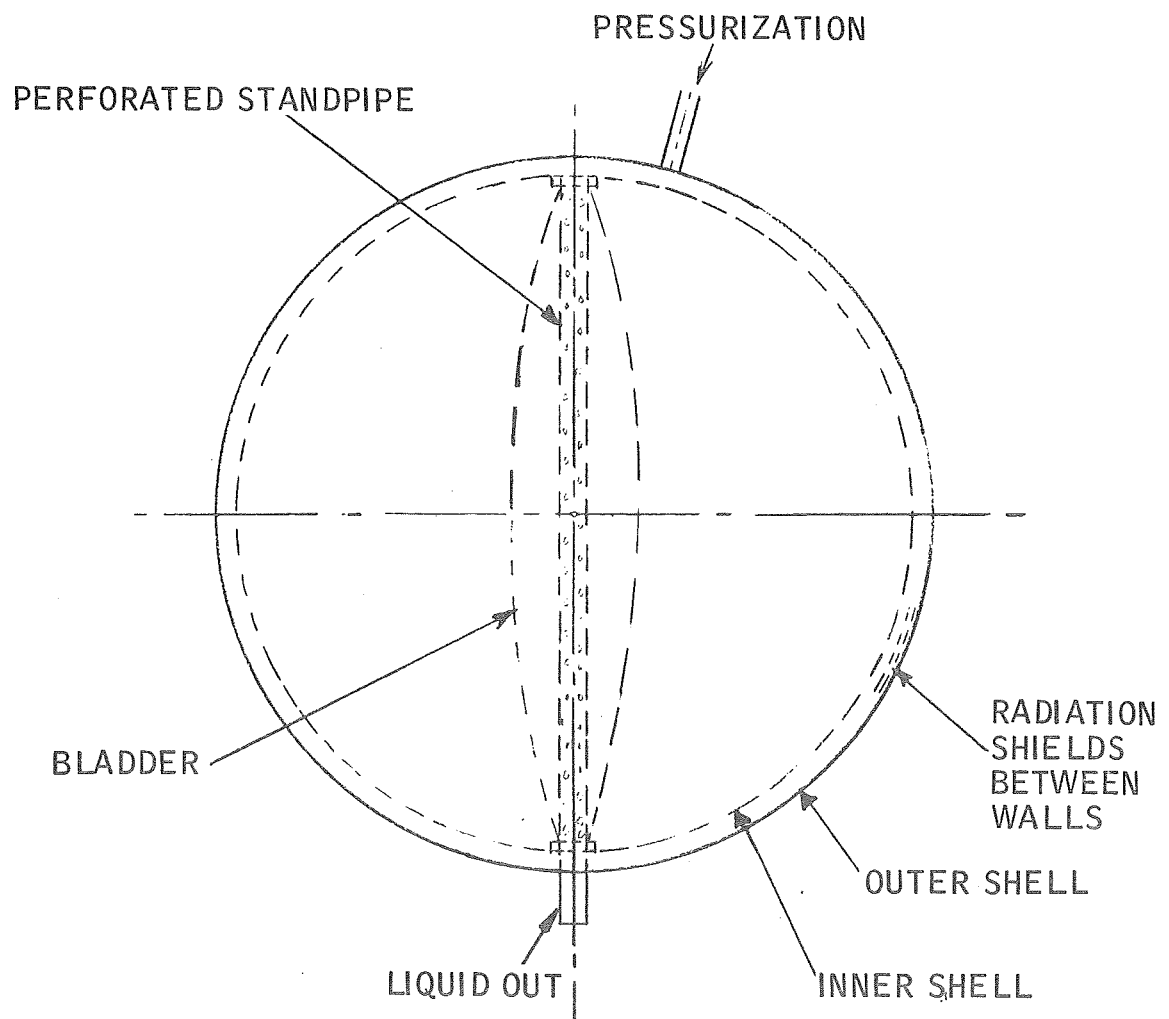


Figure 3-7. External Pressurized Bladder

It is felt, however, that there is still some question as to whether present safety requirements would allow the use of such bladders for LO<sub>2</sub> service, since the Mylar is not basically LOX compatible and the Kapton system did exhibit burning in one test. Also the length of exposure to LO<sub>2</sub> has an effect on increasing the material impact sensitivity and full quantitative evaluation of this effect has not been demonstrated to-date.

The main problem with developing suitable bladder systems for LH<sub>2</sub> has been permeation and interply inflation. Interply inflation is caused by gas being trapped within the plies at cryogenic temperatures such that when the system is warmed back to ambient the gas expands and causes separation failure of the plies.

Initially, development of a single ply bladder for the LH<sub>2</sub> service was attempted but was not successful. At present the Boeing Co. is under contract to NASA LeRC to develop an impermeable but flexible membrane to be used in conjunction with the polymeric materials. According to Reference 20 this program looks promising and it is felt that a satisfactory system can be developed.

The total number of predictable cycles for this hydrogen system is estimated at two to three with an ultimate of five.

It is noted that the bladder system shown in Figure 3-7 is of the collapsing type where pressurization is applied external to the bladder and the liquid to be expelled is internal. This is preferred for the following reasons, as summarized from Reference 22.

1. Internal pressurization would tend to trap propellant between the bladder and the tank wall thus reducing expulsion efficiency.
2. At initial loading the internally pressurized bladder is folded around the standpipe, resulting in a folded and creased bladder that is then subjected to the booster vibrational environment such that bladder flexural failure may occur.
3. Significantly more analytical and operational knowledge is available on externally pressurized bladders.

At one stage in the development it was thought that an expanding bladder would eliminate the interply inflation problem, however, subsequent testing (Reference 17) showed this to be untrue and the latest recommendation is for the collapsing type.

Based on a perusal of the data from References 13 through 22 the expected weight, expulsion efficiency and volumetric efficiency for the 42.5 ft<sup>3</sup> tank application were estimated to be 40 lb, 98% and 98% respectively. Weight is based on using a bladder consisting of 10 plies of .5 mil Kapton where the standpipe and associated hardware represent 85% of the total system weight.

3.2.2.2 Metallic Bellows. Although these systems are in general heavier than other systems, they have the advantage of operation over a significant number of expulsion cycles. Also, by measuring the stroke of the bellows the fluid quantity remaining can be quite accurately determined, even at low-gravity. A typical system which was considered in the present study is shown in Figure 3-8.

The pressurant storage is assumed to be contained within the overall tank envelope in order to increase the volumetric efficiency of the system. This configuration is similar to that tested under contract NAS3-12017 (Reference 26).

The two main types of bellows presently available are welded and formed. The welded bellows are not recommended for the present program. The main disadvantages of the welded type are that the extensive welding required makes these bellows difficult to clean, inspect and prevent leakage. Also the life expectancy is in general less predictable and they are more expensive than the formed type. Initially, the primary advantage of the welded type was a high expulsion efficiency. New formed bellows designs have, however, been developed having essentially as high expulsion efficiencies as the welded types. Pertinent data used in estimating weights, expulsion and volumetric efficiencies and state-of-the-art of these systems were obtained from References 20 through 29.

The design illustrated in Figure 3-8 utilizes the nested type of formed bellows for potentially high reliability and high expulsion efficiency. These bellows are described in References 24 and 27 and are similar to those used in the test program described in Reference 26.

Such bellows have previously been used fairly extensively for expulsion of storable fluids, as in the Minuteman Program (Reference 28). In addition, several development programs have been accomplished or are under way to provide reliable bellows systems for use with cryogenics. As an example, testing was performed on a 7" x 11" bellows where more than 100 cycles were accomplished with LN<sub>2</sub> (Reference 23). It is noted that this particular bellows was of the welded type.

Testing was also accomplished on the nested formed type of bellows described in Reference 24 using LH<sub>2</sub>. This test program, performed on a 13.5" diameter bellows, is described in Reference 26. The first bellows tested developed a leak during LN<sub>2</sub> and LH<sub>2</sub> checkout testing. A second bellows was tested and successfully completed 50 expulsion cycles (100 reversals) before a leak was detected, ( $2 \times 10^{-5}$  scc He/sec). Failure was assumed to occur when the leak rate exceeded  $10^{-6}$  scc He/sec. The program target was 100 complete expulsion cycles. A failure analysis of the bellows correlated the leaks with regions of corrosion found within the bellows. These are believed to be the result of inadequate cleaning procedures, and/or the use of tap water in some of the test operations. It is felt that these deficiencies can be overcome in the future.

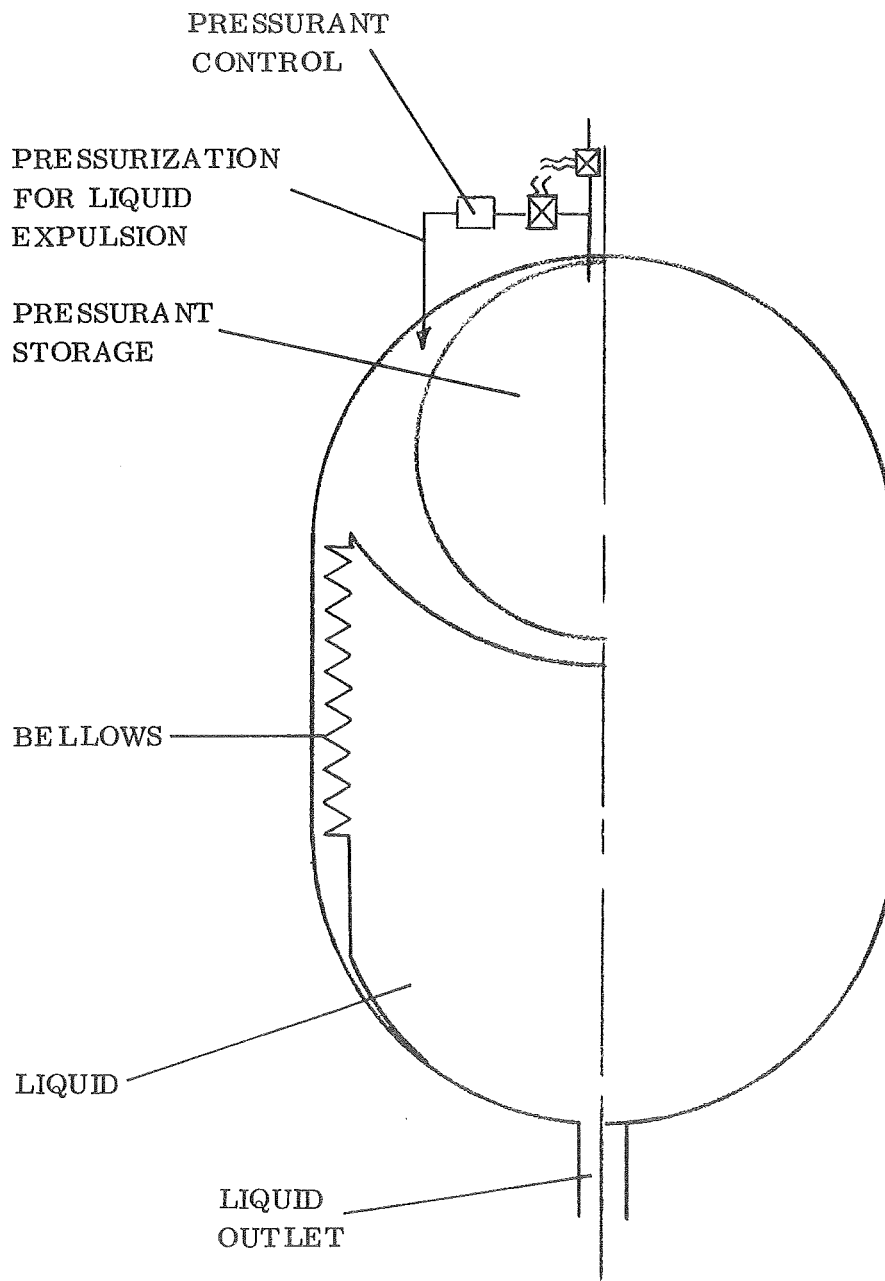


Figure 3-8. Bellows Expulsion System



At present it is considered that the main problem needing further testing is associated with rubbing or impacting of the bellows convolutions on the container wall under vibration and expulsion dynamic conditions. Such interference conditions tend to reduce the bellows life. Several programs are presently underway to provide further cryogenic design data for the bellows system. One such program is being conducted by Bell Aerosystems under contract NAS3-13327. Under the program bellows fatigue and life data will be generated under realistic dynamic loadings to be expected in operation. It is felt that such data are only needed for the proper design of cryogenic bellows and that the feasibility of such systems for greater than 100 cycles will not be a basic problem (Reference 28).

At present, bellows diameters up to 4 ft are fairly standard. Total volumes of such bellows would be on the order of 40 to 50 ft<sup>3</sup>. Further tooling developments would need to be provided for developing larger size systems. According to Reference 25 bellows diameters up to 50 ft have been advertised.

Weight and efficiency data are presented in Tables 3-2 and 3-3. It is noted that a significant weight penalty is paid by this system due to its fairly low volumetric efficiency and the fact that an essentially cylindrical tank rather than spherical is required as the basic container. Based on a direct comparison of cylindrical versus spherical tank weights it was estimated that the use of the cylindrical tank would increase the container weight by approximately 25% over that of the basic spherical system.

3.2.2.3 Diaphragms. Development work has been accomplished on both non-metallic and metallic diaphragms. Data applicable to the general evaluation of such systems has been obtained primarily from References 20, 21, 22 and 30 through 34. Recent testing accomplished by Boeing under contract NAS3-12204 on polymeric positive expulsion diaphragms for cryogenics was not successful in that the configuration tested did not collapse properly to expel the LH<sub>2</sub> (Reference 20). The diaphragm collapsed into a cone shape and then became rigid. It was felt that a satisfactory shape could have been developed, however, it is also felt that due to high flange weights and sealing problems that such systems would not be practical beyond diameters of about 24" (Reference 20).

The system felt to be most applicable to the present program is one using a metallic diaphragm and operating as shown in Figure 3-9. Significant development and testing of such systems has been accomplished by Arde Inc. of Paramus, N.J. Pertinent data are presented in References 31 through 34. The system basically consists of a thin metallic shell with wire rings brazed circumferentially at controlled intervals on the shell. The wire rings are used to stabilize the folding pattern in order to allow multiple expulsions to be accomplished. The diaphragm is integrally welded into the storage bottle.

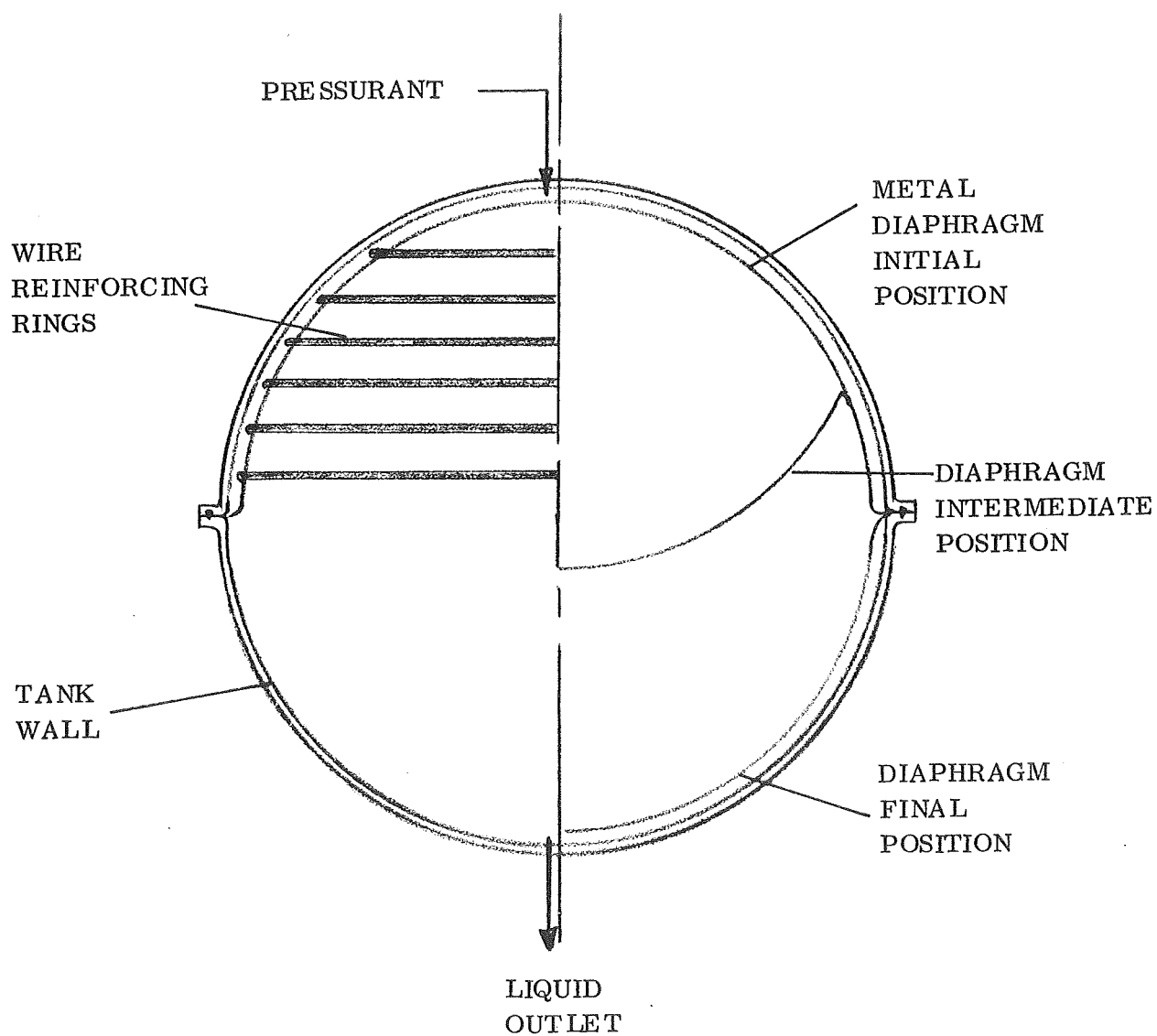


Figure 3-9. Metallic Diaphragm System

Testing to-date has shown that approximately the same number of reversals can be obtained at cryogenic temperatures as at ambient. Seven reversals have been obtained with LH<sub>2</sub> using a 24 inch diameter system and a program is presently underway under contract NAS3-12026 to improve the design to allow an increase in the number of cycles. Up to eleven reversals have been accomplished to-date on an 13.5" diameter system at room temperature. Additional fabrication and satisfactory testing have been performed on systems up to 6 ft in diameter. It is felt that with present technology diameters up to 90 inches are attainable.

It is noted that with the proper plumbing arrangement each reversal could be designed to accomplish a liquid expulsion cycle. For purposes of the present comparisons the maximum number of repeatable cycles was estimated to be five. Weight and performance data as applied to the 42.5 ft<sup>3</sup> tank application are presented in Tables 3-2 and 3-3.

**3.2.3 DYNAMIC FORCE SYSTEMS.** The fluid vortexing method of dynamic liquid control was chosen as that most applicable to the space station resupply from a shuttle vehicle. Linear acceleration or rotation of the entire shuttle and station was not considered practical. Rotation of the bottle within the payload is possible, but was not considered desirable in comparison with fluid vortexing due to the requirement for a stationary to rotating connection.

Two basic methods can be considered for applying a vortex motion to the tank fluid. These are illustrated in Figure 3-10 and 3-11. The system shown in Figure 3-10 uses an internal paddle to provide a positive vortexing action to the fluid while the system of Figure 3-11 removes fluid from the tank and tangentially injects a portion of it back into the tank to provide the required vortexing.

The paddle system has the advantage of reduced residuals and the disadvantage of fairly large hardware weight with the requirement for an internal tank motor or a tank pass-through for applying rotational motion to the paddle. The injection pumping scheme will have a minimum hardware weight, but with a likely increase in total electrical power and residual liquid. Also, start up of this system may be relatively slow due to the fact that the initial fluid being injected back into the tank can be mostly vapor.

Significant quantitative analysis has not been performed on these particular systems. Some analysis has been reported on propellant tank rotation which does give an indication of the energies and forces associated with the fluid rotation problem. Typical data of this nature are contained in References 35, 36 and 37.

In general the fluid dynamics of the process are quite involved and a detailed analysis of the system is not within the scope of the present screening task.

Weight, power and fluid residuals were, however, estimated on an order of magnitude basis in order to determine whether the vortexing system could in any way be

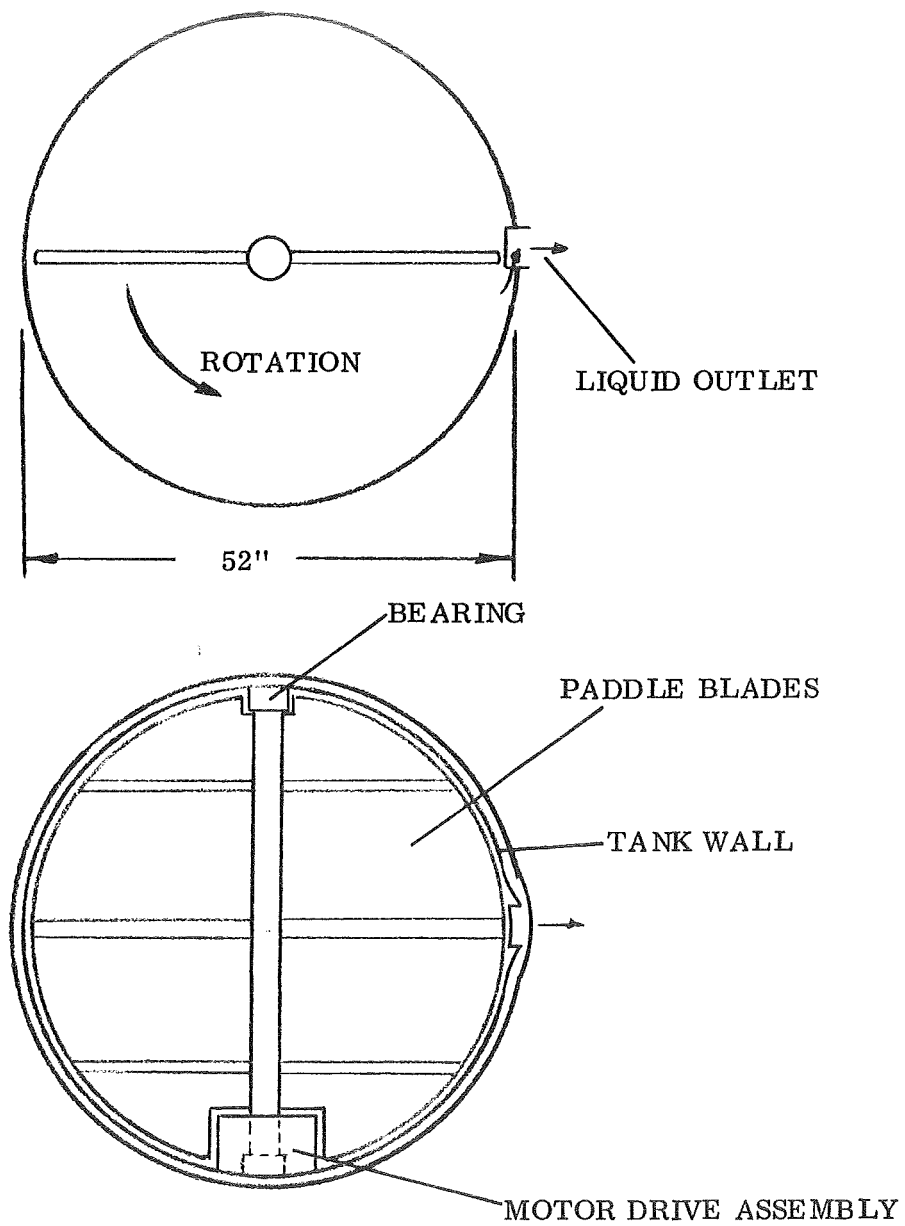
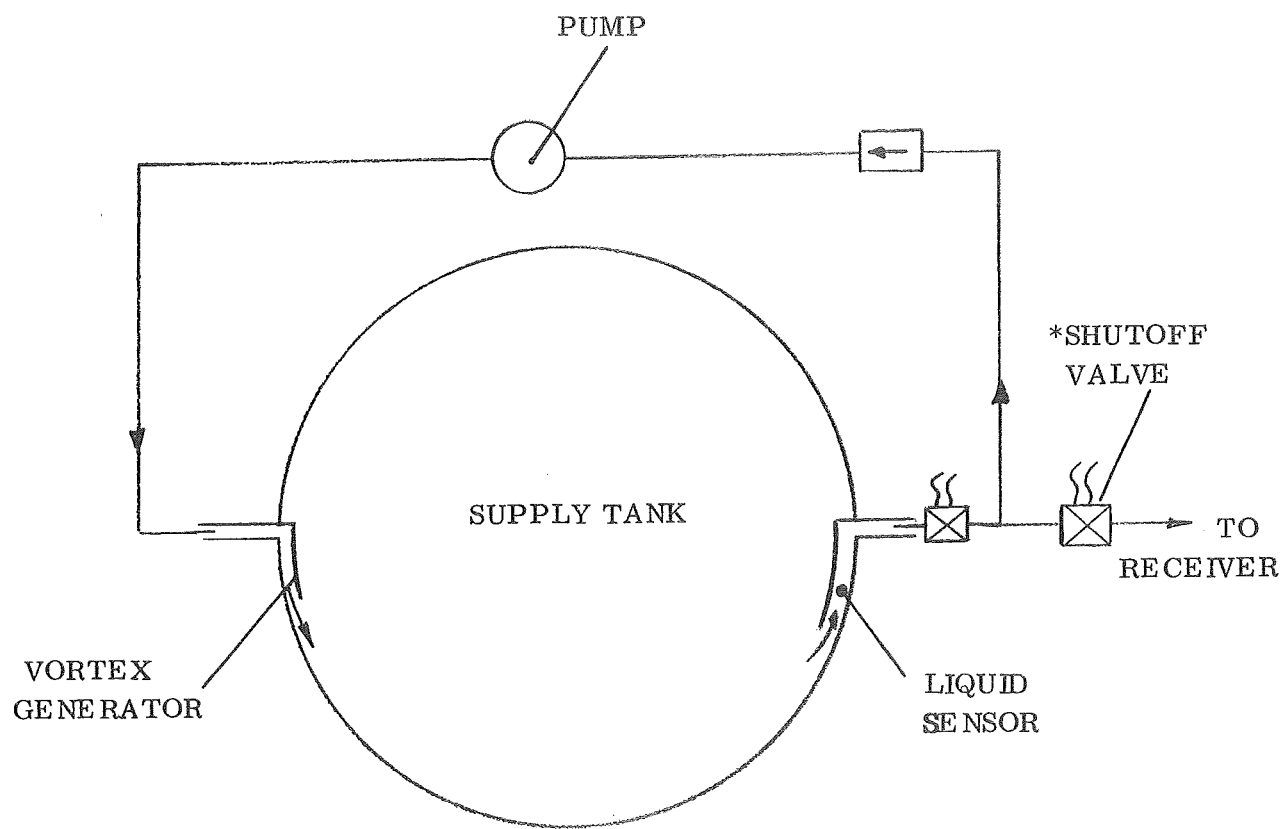


Figure 3-10. Paddle Type Vortex System



\*This valve remains closed until vortex is fully developed.

Figure 3-11. Jet Type Vortex System

competitive with other methods of transfer being considered. Due to its relative analytical simplicity the system shown in Figure 3-10 was chosen for analysis. It is realized that this system does not represent an optimum design, but should be somewhat representative of the total weight to be expected for the vortex concept.

The basic approach is to determine at what rate the fluid must be rotated in order to ensure liquid at the wall and then to determine the power and subsequent hardware weight required to accelerate and maintain the fluid at this rotation. Oxygen was taken as the critical fluid due to its relatively large mass as compared to hydrogen.

Based on the data contained in Reference 37 the rotational speed of the fluid required to maintain liquid at the wall can be estimated from the following equation.

$$\Omega_c^2 = \frac{\omega^2 \rho r_1^3}{\sigma} \quad (1)$$

where

$\sigma$  = surface tension

$\rho$  = liquid density

$r_1$  = outer radius of rotation

$\Omega_c$  = a critical rotational Weber No. defined according to Equation 1

$\omega$  = required rotational speed

Assuming solid body rotation of the fluid,  $\Omega_c$  is the critical Weber No. below which liquid will not be forced to the outer wall.

$\Omega_c$  is a function of the Bond No.,  $Bo = \rho a r_1^2 / \sigma$  and the liquid to solid contact angle. For the present case the contact angle is taken to be zero and based on;

$$\rho = 70 \text{ lb/ft}^3, a = 10^{-4} \text{ g's}, r_1 = 13 \text{ in.}, \text{ and } \sigma = 8.9 \times 10^{-4} \text{ lb/ft}$$

$$Bo = 9.25$$

Then, based on an extrapolation of the data contained in Reference 37,  $\Omega_c^2$  is estimated to have a value of 50. Then solving for  $\omega$  from Equation 1,

$$\omega = 0.13 \text{ rad/sec} = 1.25 \text{ rpm}$$

An average value of  $r_1$  was chosen for the present case in order to be conservative since the data of Reference 37 was generated for a cylinder rather than a sphere. It is noted that from Reference 37 the required angular speed decreases as the radius is increased.

A further design criteria was also considered where it was assumed that liquid must be pumped from the inner radius of the paddle to the outer radius against  $10^{-4}$  g's. From a simple force balance on a fluid element the following equation determines the required rotation rate.

$$\omega = \sqrt{a/r}$$

Assuming an inner paddle diameter of 3 inches, which is considered reasonable for the supporting shaft then.

$$\omega = .16 \text{ rad/sec} = 1.54 \text{ rpm}$$

Using this as the final design criteria and applying a safety factor of two the design rotation rate for determining power requirements was taken as 0.32 rad/sec or 3.08 rpm.

Assuming a clearance between the rotating paddle and the tank wall such that form drag on the paddle is the major retarding force then

$$F_D = C_D \rho A \frac{V^2}{2g}$$

where

$F_D$  = total drag on the paddle

$A$  = total paddle area in the direction of motion

$V$  = paddle speed, taken at the outer periphery where  $V = r\omega$ . This is a conservative assumption.

$C_D$  = drag coefficient which is a function of Reynolds No. In the present case the Reynolds No. was calculated to be sufficiently in the turbulent region such that  $C_D \approx 1.0$

Assuming this force to act entirely at the outer periphery, again a conservative assumption, the required power is determined from  $P = F_D r_1 \omega$  to be 7.3 watts.

Taking the total fluid mass as 2830 lb which assumes a 95% full 42.5 ft<sup>3</sup> tank, the energy required to accelerate to 3.08 rpm was determined from

$$KE = \frac{1}{2} W K^2 \omega^2 \quad (2)$$

where

$W$  = total fluid weight

$K$  = radius of gyration assuming solid body rotation of the liquid

$KE$  = kinetic energy

From Equation 2 the required kinetic energy was determined to be 8.5 ft-lb or 11.5 watt-sec. Assuming 7.3 watts of power continuously applied to the paddle then approximately 1.6 seconds would be required for start up, which is a very small time when considering the overall transfer process. The basic power supply was assumed to be fuel cells with the following weight assessments.

94 lb/kw plus 2.9 lb/kw-hr

Based on a motor-drive efficiency of 50% (14.3 watts of continuous motor input power required) and a maximum transfer time of 24 hours the total power supply weight was calculated to be only 2.4 lb. Therefore the power requirements of the system are relatively low and the main weight associated with this system can be attributed to fluid residuals and motor, gear box and paddle assembly weights. It is noted that the large speed reduction and associated gearing required will result in the main weight penalty associated with the motor-drive system. The basic volumetric efficiency of the system for use in a 52 inch diameter tank was estimated to be 98% and the hardware weight, including motor and gearing was estimated to be approximately 75 lb.

For the configuration shown in Figure 3-10 it is assumed that fluid residuals will consist of that liquid which can be located between the paddle and the tank wall. Taking a 1/2" clearance between the wall and paddle an expulsion efficiency of 94% is estimated. The data are presented in Table 3-2. Calculations were also made for the liquid hydrogen case showing a slightly less power requirement and overall system weight. These data are presented in Table 3-3.

**3.2.4 EVAPORATION SYSTEM.** This system relies on evaporation of the stored liquid by the input of heat to effect transfer. In this case the fluid transferred is assumed to be in the form of a vapor. In the basic system initially considered this vapor must then be condensed to restore the fluid to its original supply condition. The system is illustrated schematically in Figure 3-12.

Weight and power calculations were initially made for liquid hydrogen transfer. Transfer is assumed to take place in 24 hours. Assuming a single 42.5 ft<sup>3</sup> tank containing 95% liquid the mass of hydrogen to be transferred is calculated to be 177 lb. Based on a simple evaporation energy balance, where the heat of evaporation ( $\lambda$ ) equals 189 Btu/lb, the required tank heating is determined to be 9,800 watt-hrs or 408 watts.



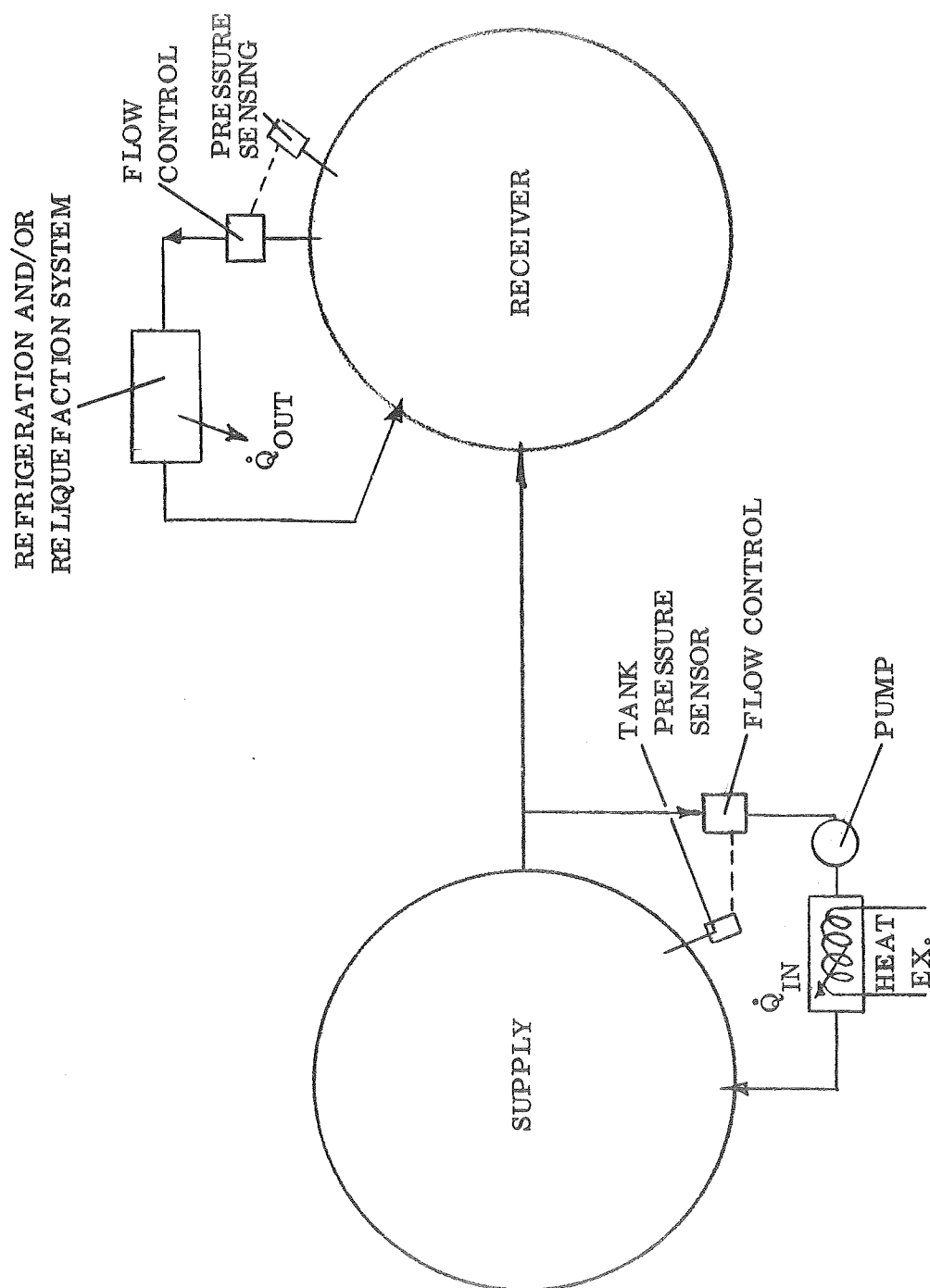


Figure 3-12. Liquid Vaporization System

Based on the power supply penalties as expressed in the previous paragraph the weight penalty for such heating would be 67 lb. In order to determine system weights for cooling the receiver the data from References 38 and 39 were used. It is assumed that a refrigeration system operating between 40°R and 500°K is required to remove the heat added due to the heating above. Solar cells aboard the space station were assumed as the power source. Assuming a completely independent closed cycle refrigeration system, then from the data of Reference 38 a total refrigeration system weight, including radiator and solar cells, was estimated to be 20,400 lb. This is considered to be an intolerable weight penalty.

Assuming that the hydrogen being transferred is used in the refrigeration cycle then a reliquefaction system requirement was determined from the data of Reference 39. For a reliquefaction of 177 lb of GH<sub>2</sub> where the GH<sub>2</sub> is initially at 40°R a minimum total weight penalty, as estimated from Reference 39, was found to be 2,660 lb. This is still considered excessive as compared to other liquid transfer systems being considered.

A further analysis was then made to determine the possibility of not condensing the transferred fluid and letting the pressure buildup in the supply and receiver bottles. Calculations for this condition indicated a potential pressure rise on the order of 1,000 psi. This puts the system in the supercritical pressure range and therefore this system will not be considered further for liquid transfer.

In the case of LO<sub>2</sub> reliquefaction of a single tank where the mass to be transferred is 2830 lb a reliquefaction system weight of approximately 5,600 lb is estimated.

3.2.5 OVERALL SYSTEM COMPARISONS AND RECOMMENDATIONS. Based on the general discussions of the previous paragraphs and an analysis of the pertinent data contained in Ref. 6 through 40, representative comparison data were generated on the various systems. These data are presented in Tables 3-2 and 3-3. The main objective was to provide data applicable to relative evaluations of the various systems within each major category rather than to obtain absolute magnitudes.

Data are presented for both oxygen and hydrogen transfer fluids. In each case a single 42.5 ft<sup>3</sup> supply tank was assumed. The hardware weight is taken to include only the fluid orientation or collection device and power supply weights required for the orientation or collection. Auxiliary system weights such as required for venting, pressurization and pumping were not included. Basic tank weights are also not included, however, differences in tank weight are estimated between the various systems. As an example, the increase in tank weight due to volumetric efficiencies less than 100% as well as that due to additional flanging required for certain systems is presented. The tank weight is taken to be proportional to the total tank volume required. The reference spherical tank weight is 225 pounds as discussed in Section 2. Also, as is the case with the bellows system, required tank shapes other than spherical will result in larger weight and is taken account of in the analysis.

Table 3-2. Subcritical System Comparison Data (42.5 Ft<sup>3</sup> LO<sub>2</sub> Tank)

	Surface Force Sys.		Positive Expulsion			Fluid Vortexing	Liquid Vaporization
	Capillary Screens	Dielectrophoresis	Bladders	Bellows	Diaphragms		
* Hardware Weight, Lb	30	40	15	72	70	75	5,600
Δ Expulsion Efficiency, %	98	99	98	98	99	94	99
** Fluid Residuals, Lb	56	28	56	56	28	168	14
+ Volumetric Efficiency, %	99.5	99.5	98	90	98	98	99.5
*** Increased Tank Weight, Lb	1	1	4	87	16	5	1
Total Weight, Lb	87	69	75	215	114	248	5,615
Total Life, Expulsion Cycles	>40	>40	25	>40	5	>40	>40
† Safety	2	4	4	2	2	2	2
† Complexity/Reliability	2	4	3	3	3	3	3
† Development Potential/State-of-the-Art	2	3	3	2	2	2	2
<p>Δ Expulsion efficiency defined as [(Fluid Loaded) - (Fluid Remaining)] / (Fluid Loaded)</p> <p>+ Volumetric efficiency defined as [(Total Tank Volume) - (Unusable Volume)] / (Total Tank Volume)</p> <p>† Relative ratings; 1 through 5 where 1 represents best. No absolute value significance intended.</p> <p>* Includes only the orientation or collection device and power supply for direct system operation.</p> <p>** Assumes initially 95% full tank of LO<sub>2</sub>.</p> <p>*** Represents additional tank weight due to less than 100% volumetric efficiency plus any increase due to required flanges or tank shapes other than spherical. Reference spherical tank weight taken to be 225 lb.</p>							

Table 3-3. Subcritical System Comparison Data (42.5 Ft<sup>3</sup> LH<sub>2</sub> Tank)

	Surface Force Sys.		Positive Expulsion			Fluid Vortexing	Liquid Vaporization
	Capillary Screens	Dielectrophoresis	Bladders	Bellows	Diaphragms		
* Hardware Weight, Lb	30	40	15	72	70	70	2,660
Δ Expulsion Efficiency, %	98	99	98	98	99	94	99
** Fluid Residuals, Lb	4	2	4	4	2	11	2
+ Volumetric Efficiency, %	99.5	99.5	98	90	98	98.5	99.5
*** Increased Tank Weight, Lb	1	1	4	87	16	5	1
Total Weight, Lb	35	43	23	163	88	86	2,663
Total Life, Expulsion Cycles	> 40	> 40	5	> 40	5	> 40	> 40
† Safety	2	2	2	2	2	2	2
† Complexity/Reliability	2	4	3	3	3	3	3
† Development Potential/ State-of-the-Art	2	3	4	2	2	2	2
Δ Expulsion efficiency defined as [(Fluid Loaded) - (Fluid Remaining)] / (Fluid Loaded)							
+ Volumetric efficiency defined as [(Total Tank Volume) - (Unusable Volume)] / (Total Tank Volume)							
† Relative ratings; 1 through 5 where 1 represents best. No absolute value significance intended.							
* Includes only the orientation or collection device and power supply for direct system operation.							
** Assumes initially 95% full tank of LO <sub>2</sub> .							
*** Represents additional tank weight due to less than 100% volumetric efficiency plus any increase due to required flanges or tank shapes other than spherical. Reference spherical tank weight taken to be 225 lb.							

It is noted that for each of the major system types listed in Tables 3-2 and 3-3 the auxiliary system requirements and design problems as to pressurization and/or pumping, thermal protection and venting, line and receiver tank chilldown and general receiver tank fluid conditioning will be similar within each category. It was therefore deemed desirable to choose a representative system from each category for further overall detail system definition, analysis and comparisons.

Based on the data presented in Tables 3-2 and 3-3 the following systems were chosen for further detail definition and analysis.

1. Surface tension or capillary containment system using screens.
2. Metallic bellows for positive expulsion.
3. Fluid vortexing within a restrained tank in order to orient the liquid at the outer periphery for transfer.

The surface tension system was chosen over the dielectrophoretic surface orientation system primarily on the basis of potential safety. Weights and state-of-the-art of the two systems are comparable, however, for use in oxygen there is still some question of electrical breakdown and associated combustion hazard associated with the dielectrophoretic system.

In the case of the positive expulsion methods the metallic bellows was chosen as the only system potentially capable of meeting the number of expulsion cycles desired (40 cycles) for the station resupply application. Also, even though somewhat heavier than other methods the potential of developing a reliable and predictable system for use with cryogenics is felt to be higher with the bellows system. It is noted that other methods such as metallic and/or non-metallic diaphragms and bladders can be considered and compared with the bellows system even though not having a total life comparable to that of the station. This comparison would be on the basis of total cost and would take account of replacing such systems or expulsion components after a number of flights. The impact on the total transfer operation of developing such positive expulsion systems will be assessed and reported as part of the detail analysis and comparison tasks.

The fluid vortexing method of dynamic liquid control is seen to represent a weight penalty in the case of LO<sub>2</sub> transfer when compared to other systems. This is due primarily to the fairly high residuals associated with this system. In the case of hydrogen transfer the weight is comparable to the other systems. In any case when considering overall safety and development potential or state-of-the-art this system is considered representative enough to justify further detail analysis.

Due to the very high weight involved the liquid vaporization system will not be considered further.

## PROGRAM COST DATA

The following cost data estimates are presented as required by the NAS8-26236 contract document. All costs are approximate and are without fee.

1. Expenditures to date: \$500.00
2. Estimated funds to completion: \$32,466.00
3. Problem areas: None

## WORK TO BE PERFORMED

During the next month development will be initiated on a computer program to be used in performing the overall energy balance calculations associated with the high pressure transfer systems. Set-up and check-out of the receiver tank two phase chilldown program will also be accomplished for application to orbital propellant transfer calculations. The above work is being accomplished under the Convair IRAD program.

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